FUNDAMENTALS OF HYDRAULIC ENGINEERING SYSTEMS - 5TH Edition

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Pearson/Prentice Hall

Chapter 6

Water Flow in Open Channels

Energy Principles in Open Channels

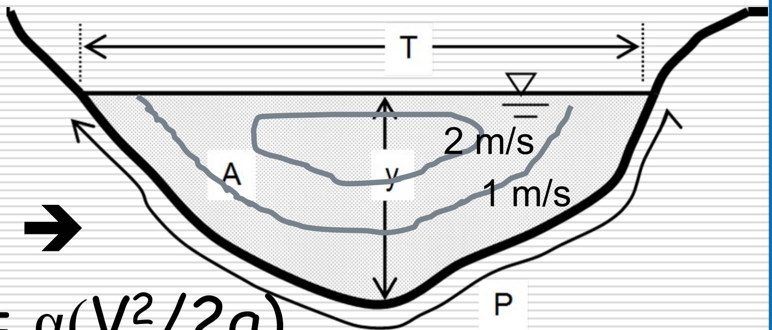
(Three Forms of Energy per Unit Weight)

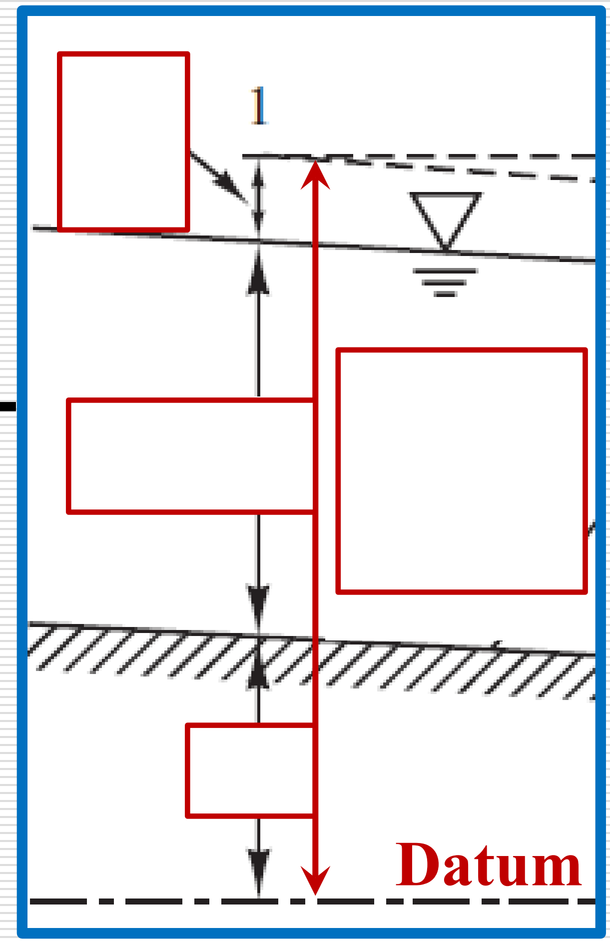
Like pipe flow, the energy forms are:

Potential, Pressure, and Kinetic

and expressed as energy head: ➔

Position + Pressure + Velocity = H





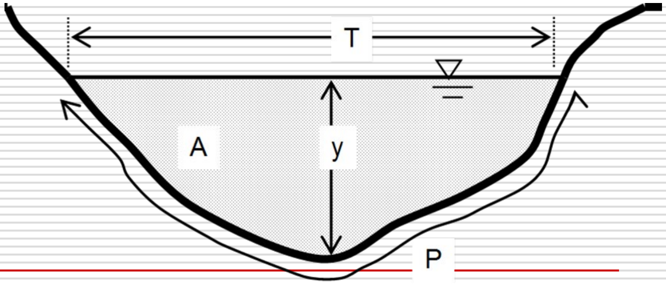
Since V varies across channel ➔

Avg "V" Head = $\alpha(V^2/2g)$

where α = energy coef. (1.05 to 1.20)

Also, p/γ can vary if bottom slope is not constant due to centrifugal force.

Hydraulic Efficiency in Open Channels



Recall Manning's Eq'n: $Q = AV = (k_M/n)AR_h^{2/3}S_e^{1/2}$

Based on this equation, how would we maximize Q for a given slope and "n" value? **Ans:**

Alternatively:

Which of the shapes below is most efficient?

Is that shape practical? Why? Note the best alternatives.

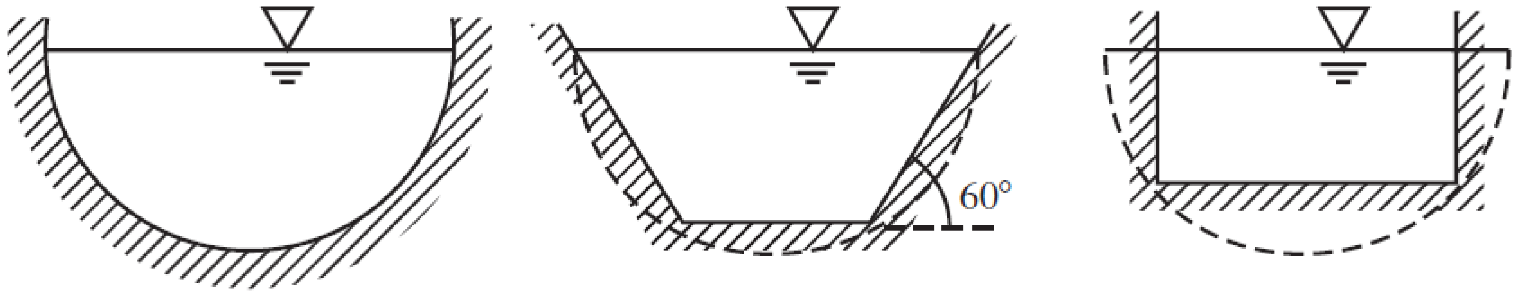
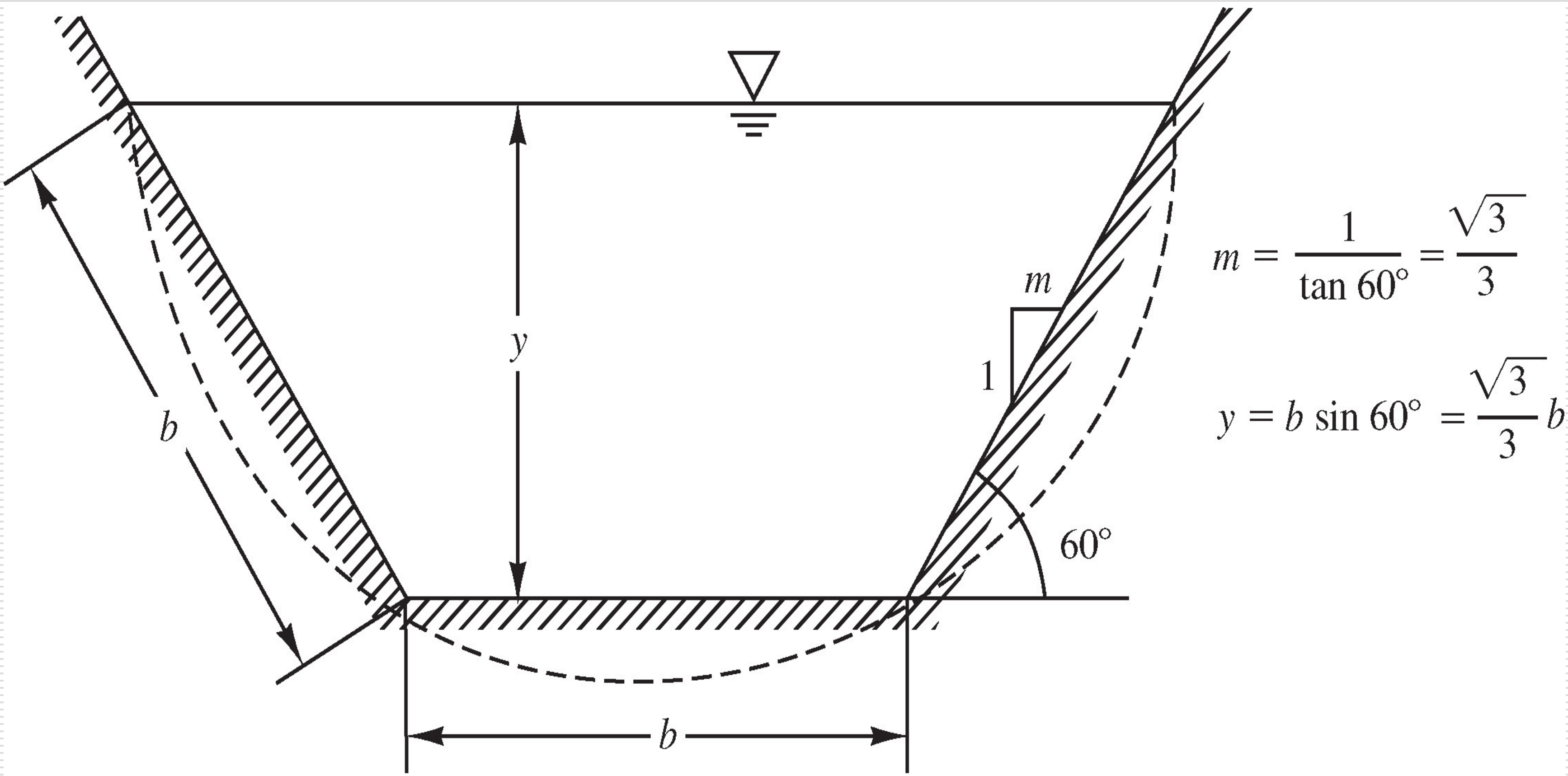


Figure 6.5 Hydraulically efficient sections

Figure 6.6 Best hydraulic trapezoidal section
{see demonstration of the BH Trapezoidal section or half-hexagon)



Specific Energy in Open Channels

(Interrelationships Between Energy Forms)

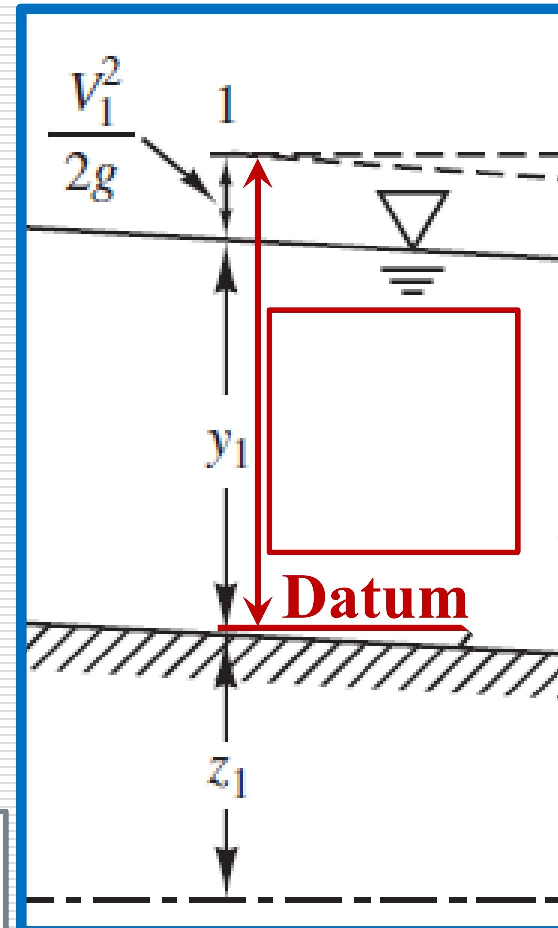
Total Energy Head in Open Channels:

$H = z + y + V^2/2g$ → arbitrary datum

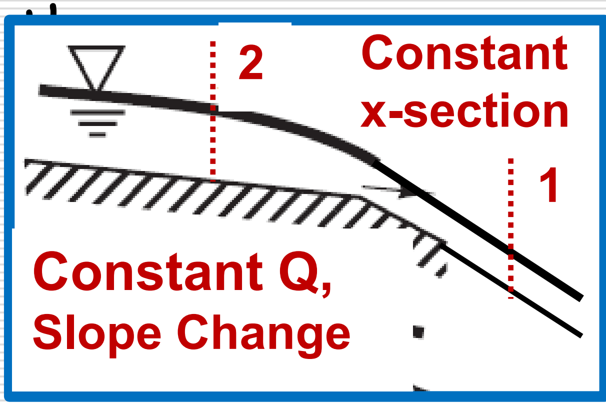
However, **specific energy** head is:

$E = y + V^2/2g = y + Q^2/(2gA^2)$ →

when the channel bottom is the datum.

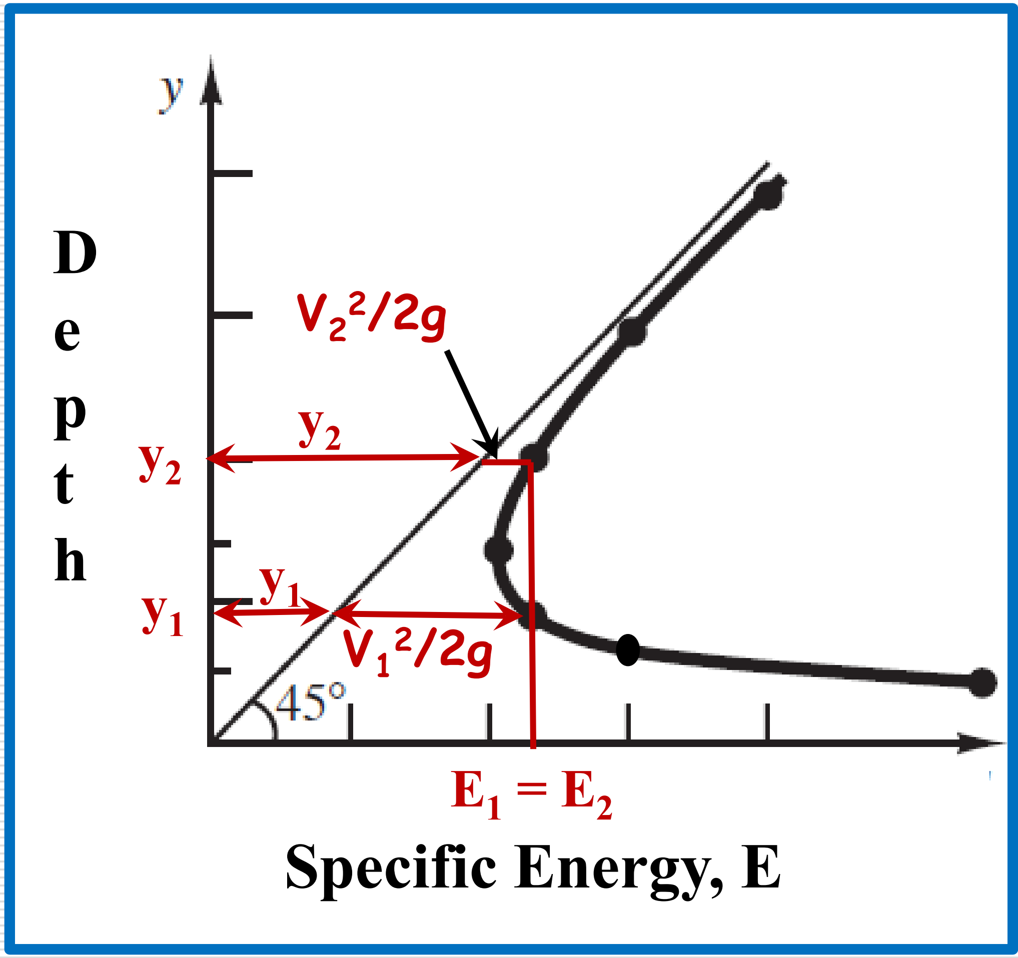


If $E_2 = E_1$ below (minimal losses), how do the specific energy components change from Section 2 to 1?



Specific Energy Curves

(Flow Regimes & Alternate Depths)



$E = y + Q^2/(2gA^2)$

For a constant Q, plotting "E" vs. a varying "y" (depth) of a given X-section yields:

← **Specific Energy Curve**

Observe that 2 different flow conditions occur at most energy levels, $E_1 = E_2$

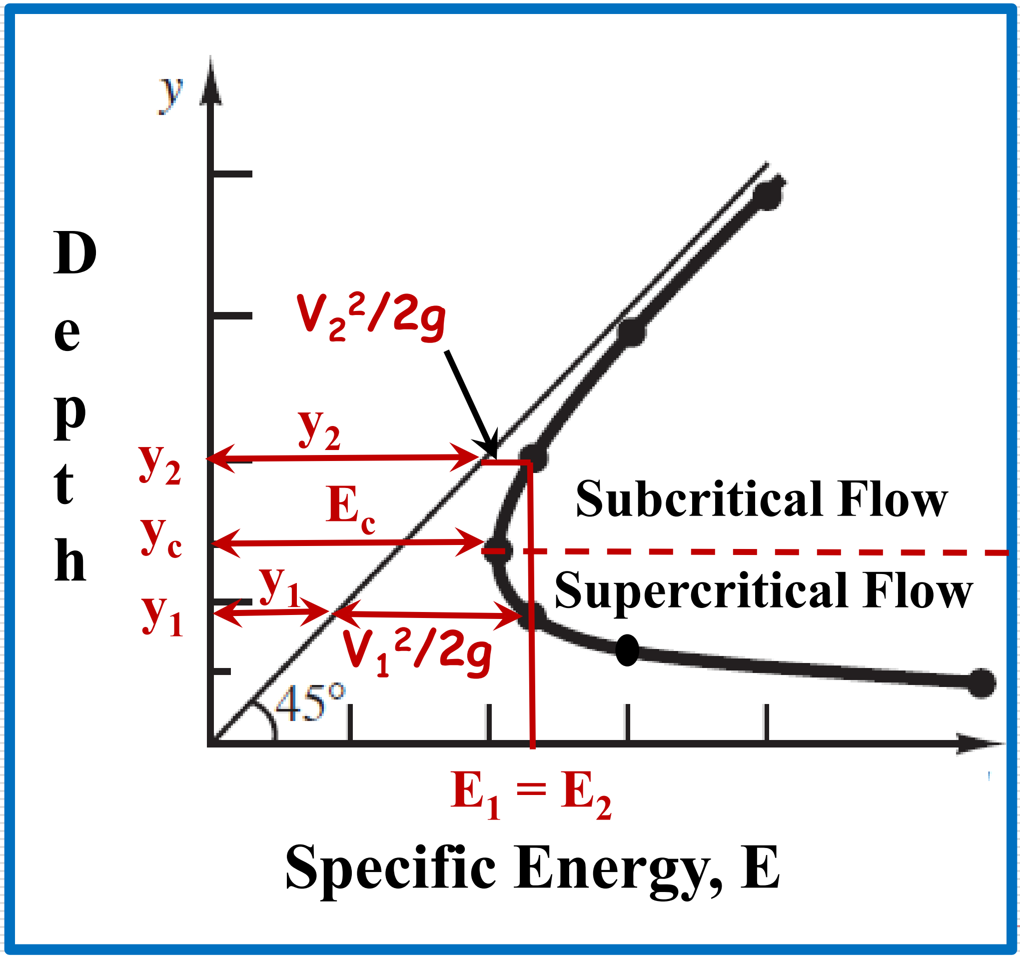
E_1 → low depth, high V

E_2 → high depth, low V

Alternate depths: y_1 & y_2

Minimum Energy and Critical Depth

(Subcritical and Supercritical Flow)



At one location, the energy is a minimum (E_c ➔ **critical flow**) and the depth is called **critical depth** (y_c).

It separates flow regimes:

Supercritical Flow:

E_1 ➔ low depth, high V

Subcritical Flow:

E_2 ➔ high depth, low V

Steep channel slopes will produce supercritical flow.

Critical Depth & the Froude Number

(Minimizing Specific Energy in a Channel)

To find y_c, set the 1st derivative of E equal to 0: **$dE/dy = 0$**

$$dE/dy = d/dy\,[y + Q^2/2gA^2] = 1 - [2Q^2/2gA^3](dA/dy) = 0$$

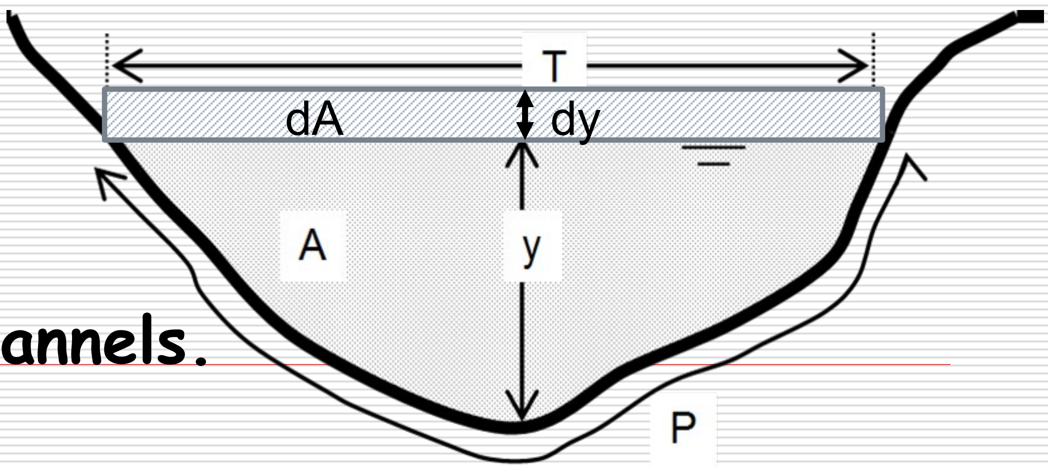
Note from the figure that $dA/dy = T$. Substituting yields,

$1 = Q^2T/gA^3$ ➔ Also, $A/T = D$ (hydraulic depth). Thus,

$1 = Q^2/(gDA^2) = V^2/gD$ or $1 = V/(gD)^{1/2} = N_F$ ➔ **Froude Number**

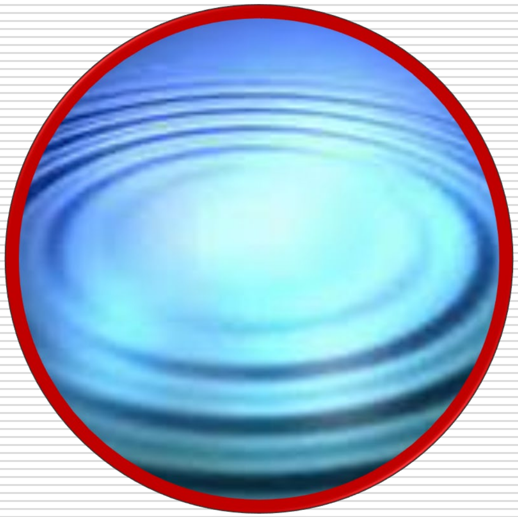
Rectangular channels:
$y_c = (q^2/g)^{1/3}$; $q = Q/b$
and b = channel width.

Use: $Q^2/g = A^3/T = DA^2$
to find y_c for **all other channels**.



Froude Number and Critical Depth

(Rectangular and Non-rectangular Channels)



N_F → **Ratio of inertial to gravity force.**

Alternatively, the ratio of **flow velocity** to the **velocity of a disturbance wave**.

← Disturbance wave (throw stone in pond)

$N_F = V/(gD)^{1/2} = 1$ (critical flow). Thus the channel velocity equals the wave speed.

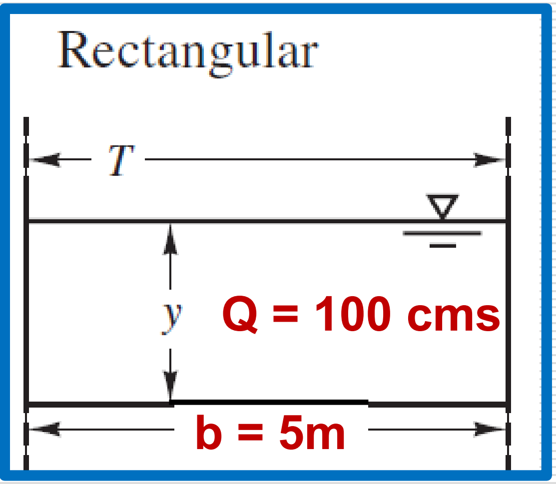
$N_F < 1$ (subcritical flow) → The channel velocity (V) is less than the wave speed $(gD)^{1/2}$ (i.e., throw a stone into channel and the disturbance wave will propagate upstream).

$N_F > 1$ (supercritical flow) Disturbance wave washes away.

Critical Depth & Froude Number

(Example Problem – Rectangular Channel)

Given: Concrete channel with $S_o = 0.01$ ➔



Find normal & critical depths & N_F.

From Table 6.2: n = 0.013, & Table 6.1:

A = [ ] P = [ ] Find d_n:

$Q = (1/n)AR_h^{2/3}S_o^{1/2} = (1/n)(A^{5/3}/P^{2/3})S_o^{1/2}$

Hence, $Qn/S_o^{1/2} = (100*0.013)/(0.01)^{1/2} = (5y_n)^{5/3}/[5+2y_n]^{2/3}$

Solving iteratively (or w/charts or software), $y_n = 2.31$**m**

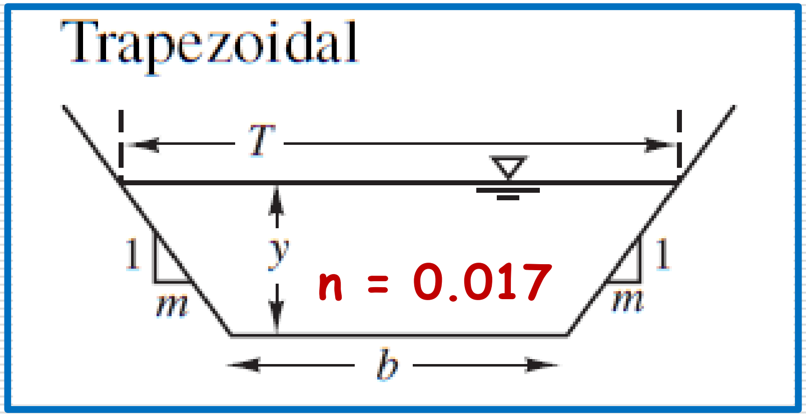
$V = Q/A =$ [ ] $D = A/T =$ [ ] $N_F = V/(gD)^{1/2} =$ [ ]

Flow is supercritical since $N_F > 1$. $q = Q/b =$ [ ]

$y_c = (q^2/g)^{1/3} = (20^2/9.81)^{1/3} =$ [ ] **Note: $y_n < y_c$**

Critical Depth & Froude Number

(Example Problem → Trapezoidal Channel)



Given: Channel w/Q = 1510 cfs

S_o = 0.00088, m = 1.5, b = 25 ft

Solution: From Table 6.1:

A = [ ] T = [ ] Thus,

A = y(25 + 1.5y) T = 25 + 3y. At critical depth: $Q^2/g = A^3/T$

$Q^2/g = (1510)^2/32.2 = 70{,}800 = [y_c(25 + 1.5y_c)]^3/[25 + 3y_c]$

Solving iteratively (or w/charts or software), **y_c = 4.41 ft**

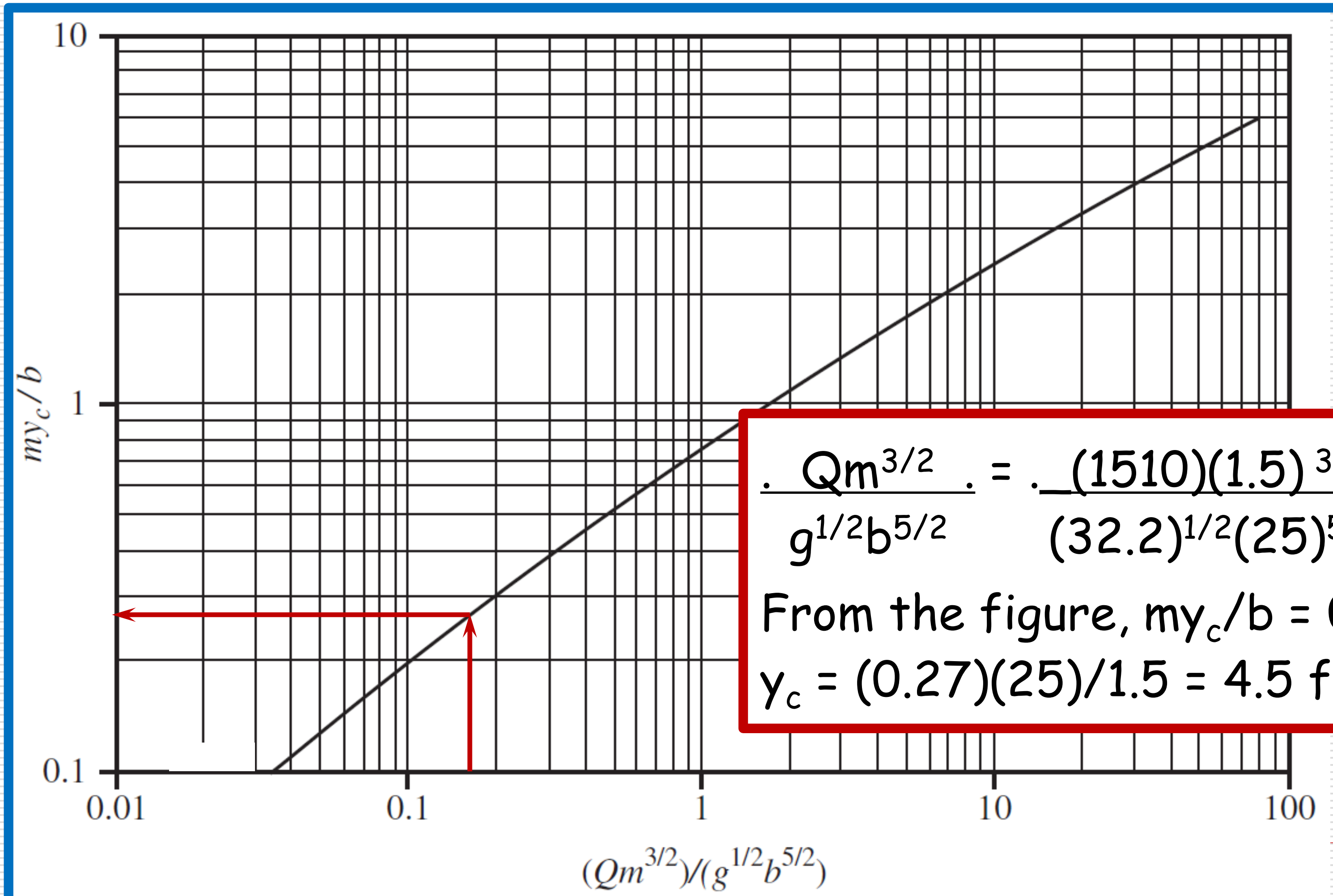
Recall from previous class for this channel: y_n = 6.25 ft

Since $y_n > y_c$ → **Flow is** [ ]

Alternative Solution

(Trapezoidal Channel, Fig. 6.9a)

Homework Problems:



$$\frac{Qm^{3/2}}{g^{1/2}b^{5/2}} = \frac{(1510)(1.5)^{3/2}}{(32.2)^{1/2}(25)^{5/2}} = 0.16$$

From the figure, $my_c/b = 0.27$

$y_c = (0.27)(25)/1.5 = 4.5$ ft

Figure 6.9b Critical depth solution for circular sections

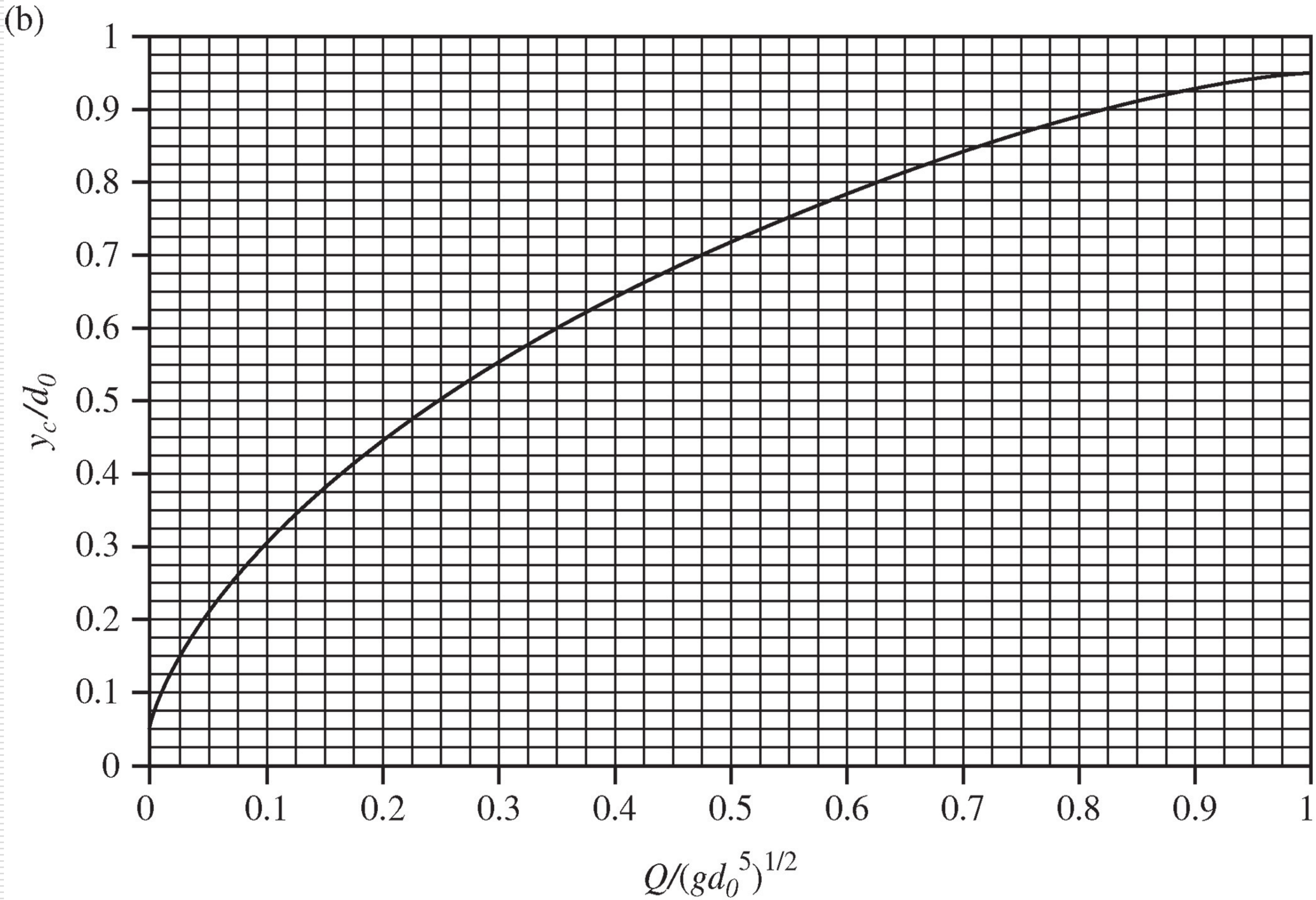


TABLE 6.6 Stable Side Slopes for Channels

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Material	Side Slope[a] (Horizontal:Vertical)
Rock	Nearly Vertical
Muck and peat soils	$^1/_4$:1
Stiff clay or earth with concrete lining	$^1/_2$:1 to 1:1
Earth with stone lining or earth for large channels	1:1
Firm clay or earth for small ditches	1 $^1/_2$:1
Loose, sandy earth	2:1 to 4:1
Sandy loam or porous clay	3:1

[a] If channel slopes are to be mowed, a maximum side slope of 3:1 is recommended.

Source: Based on V. T. Chow, *Open Channel Hydraulics* (New York: McGraw-Hill, 1959).

TABLE 6.7 Suggested Maximum Permissible Channel Velocities

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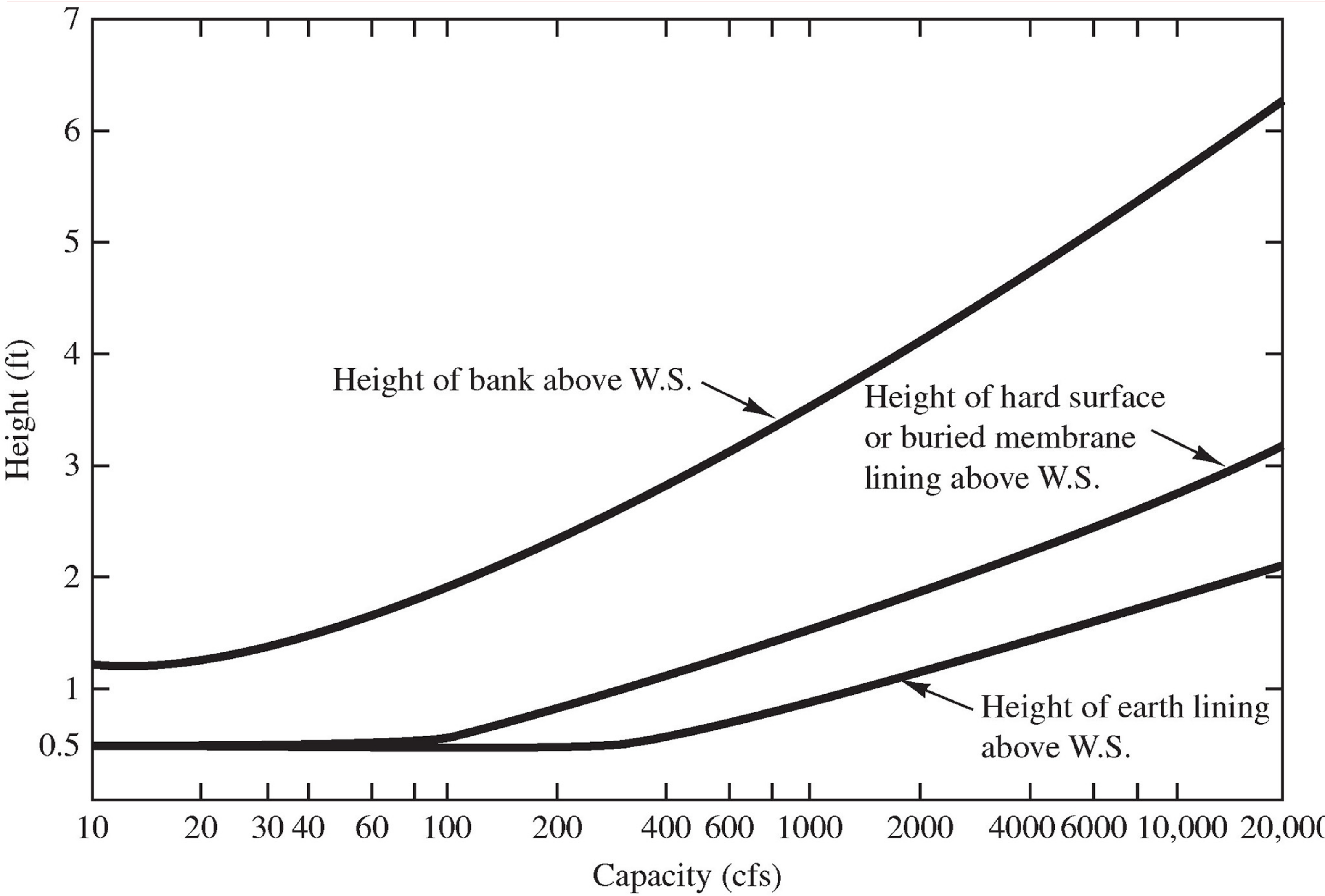
Channel Material	V_{max} (ft/s)	V_{max} (m/s)
Sand and Gravel		
Fine sand	2.0	0.6
Coarse sand	4.0	1.2
Fine gravel[a]	6.0	1.8
Earth		
Sandy silt	2.0	0.6
Silt clay	3.5	1.0
Clay	6.0	1.8

[a]Applies to particles with median diameter (D_{50}) less than 0.75 in (20 mm).

Source: U.S. Army Corps of Engineers. "Hydraulic Design of Flood Control Channels," Engineer Manual, EM 1110-2-1601. Washington, DC: Department of the Army, 1991.

Figure 6.15 Recommended freeboard and height of banks in lined channels.
Source: U.S. Bureau of Reclamation, Linings for Irrigation Canals, 1976.



Supercritical Flow on a Spillway

Fresno Dam, Montana (USA)

Rf.➔http://www.usbr.gov/projects/Facility.jsp?fac_Name=Fresno+Dam